S-Band Receiver Third-Order Loop Demonstration

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In mid-April 1972, the Mariner Mars 1971 spacecraft began encountering high doppler rates under weak signal conditions. The Block III receiver was dropping lock, resulting in lost data. This article describes a third-order tracking filter which was designed for the Block III receiver and successfully demonstrated at DSS 14.

I. Introduction

The *Mariner* Mars 1971 spacecraft has pushed the DSIF tracking system into a new era. Currently, the mission dynamics are such that S-band doppler rates of 25 Hz/s and doppler acceleration as high as 0.16 Hz/s have been experienced. The Block III DSIF receiver cannot track doppler rates greater than 10 Hz/s with the current signal margin (8 dB).

It was decided to design and build a third-order loop filter for the Block III DSIF receiver. The receiver using the third-order loop has two bandwidths (5 and 10 Hz) and is capable of tracking doppler rates in excess of 1000 Hz/s and will stay locked with doppler acceleration as high as 3.8 Hz/s^2 as demonstrated by tests at CTA 21 (see Fig. 1).

The immediate response from DSS 14 operations was that the third-order loop solved the tracking problem. It was noted, however, that the initial frequency acquisition was more difficult. A trip was made by the designer to DSS 14 to watch an operational acquisition of the *Mariner* Mars 1971 spacecraft with the third-order loop. It was apparent that part of the problem was the operator's continuous tuning of the voltage-controlled oscillator (VCO). While this procedure has worked well for the second-order loops, it is inappropriate for the third-order loop due to the added "memory" inherent in the added integrator.

It was found that when the third-order loop was within 200 Hz (at S-band) that loop would acquire within 60 seconds. When frequency predicts were used, acquisition occurred within 15 seconds.

Acquisition with the high doppler rates (i.e., 30 Hz/s present when the uplink is being swept) is a more difficult problem. This appears to be too great a doppler rate for an unassisted acquisition, even for a third-order loop. This presents a problem since the receiver operator has no good indicators of when he is "oversteering" the third-order loop, and acquisition under these conditions seems unreliable.

The answer to the problem seems to be a *hybrid loop*—a device that can acquire as a second-order loop and automatically switch to the third-order configuration to track. A filter of this type has been designed and tested at CTA 21 (see Fig. 2).

II. Design Approach

A. Third-Order Loop Filter

The open-loop transfer of the third-order loop filter (see Fig. 1) is

$$H(s) = \left[\frac{R_2 + R_3}{R_1}\left(\frac{1 + SC\dfrac{R_2R_3}{R_2 + R_3}}{1 + SCR_3}\right)\right]^2$$

$$\approx \left[\frac{R_2 + R_3}{R_1}\left(\frac{1 + SCR_2}{1 + SCR_3}\right)\right]^2$$

$$= \left(K_1 \frac{(1 + T_2S)}{1 + T_1S}\right)^2$$

The design approach has been to select the design that satisfied the doppler and doppler rate input with the minimum time constant T_1.

Define

$$q = \alpha AK_d\,(\text{volts/deg})\,K_v\,(\text{Hz/volt})\,K_m$$

$$\times\, 360 \times \left(\frac{K_1}{T_1}\right)^2 T_2^3 = KK_1^2\frac{T_2^3}{T_1^2} = G\frac{T_2^3}{T_1^2}$$

$$q_0 = 6.75$$

$$W_{L_0} = \frac{4.455}{T_2}$$

$$W_L = \frac{q\,(2q + 3)}{2T_2\,(2_q - 1)}$$

$$\phi_{ss}\,(\text{deg}) = \frac{360(\Omega_0 + \Lambda t)}{G} + \frac{720\Lambda T_1}{G} + \frac{360\Lambda T_1^2}{G}$$

Let

$$a = \frac{360\,T_2^3}{q}$$

so that

$$T_1 = \frac{a\,\Lambda}{\phi_{ss}} + \left(\left(\frac{a\,\Lambda}{\phi_{ss}}\right)^2 + \frac{a\,(\Omega_0 + \Lambda t)}{\phi_{ss}}\right)^{1/2} = R_3C$$

$$T_2 = \frac{4.455}{W_{L_0}} = R_2C$$

$$R_1 = R_2\left(\frac{R_2 + R_3}{R_3}\right)\frac{\sqrt{KT_2}}{q}$$

B. Second-Order Hybrid Filter

Design for the hybrid loop was implemented by leaving the second integrator (see Fig. 2) as designed for the third-order loop (since this integrator stores the frequency offset control voltage to the VCO). The first integrator was modified to be a simple gain stage so that the second-order loop would have the same bandwidth as the third-order loop. The second-order loop is overdamped (i.e., $r_0 = 7.91$).

For second-order hybrid design,

$$H(s) = \frac{R_4}{R_1} \times \frac{R_2 + R_3}{R_1}\left(\frac{1 + \dfrac{R_2R_3}{R_2 + R_3}SC}{1 + R_3\,SC}\right)$$

$$\approx \frac{R_4}{R_1} \times \frac{R_2 + R_3}{R_1}\left(\frac{1 + SC\,R_2}{1 + SC\,R_3}\right)$$

$$= K_1\,K_2\left(\frac{1 + T_2S}{1 + T_1S}\right)$$

$$r = 360\,K_D\,(\text{volts/deg})\,K_v\,(\text{Hz/volt})\,K_m\,\alpha\,K_1\,K_2\,\frac{T_2^2}{T_1}$$

$$= G\,K_1\,K_2\,\frac{T_2^2}{T_1}$$

$$K_1 = \frac{2T_2 \times W_{L_0} - 1}{G \times \dfrac{R_2}{R_1} \times T_2}$$

but

$$R_1 = R_2\left(\frac{R_2 + R_3}{R_2}\right)\frac{\sqrt{KT_2}}{q} \quad \text{(same as standard third-order loop design)}$$

$$R_4 = R_1\,K_1$$

Whenever $R_2 << R_3$,

$$r = G\,K_1\,\frac{R_2 + R_3}{R_1} \times \frac{R_2C}{R_3C} \times T_2 \approx G\,K_1\,\frac{R_2}{R_1}\,T_2$$

and

$$W_{L_0} = \frac{r + 1}{2T_2}$$

so that

Computer programs have been written for both of the above designs utilizing the PDP-11 BASIC language.

III. Future Effort

Theoretically the acquisition characteristics for the third-order loop are much superior to the second-order loop (and may well prove to be the case when computer-controlled acquisition is available). However, in the present DSS 14 environment, it appears the hybrid loop is a better approach since it allows past experience and procedures to be used during difficult manual acquisition and then automatic switching (activated by the lock detector circuit) to use the superior tracking performance of the third-order filter. Theoretical studies are currently underway to predict the loop performance to an arbitrary forcing function.

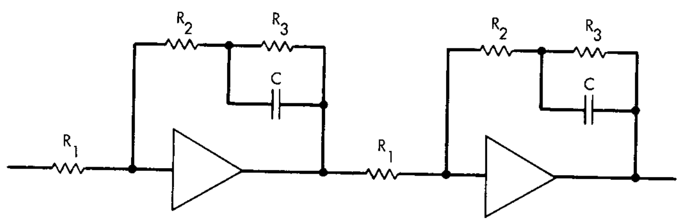

Fig. 1. Third-order filter

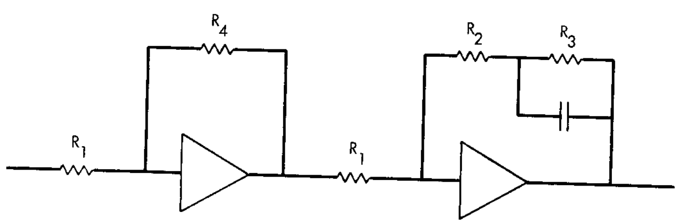

Fig. 2. Second-order hybrid filter